Charged Jet Evolution and the Underlying Event in Proton-AntiProton Collisions at 1.8 TeV

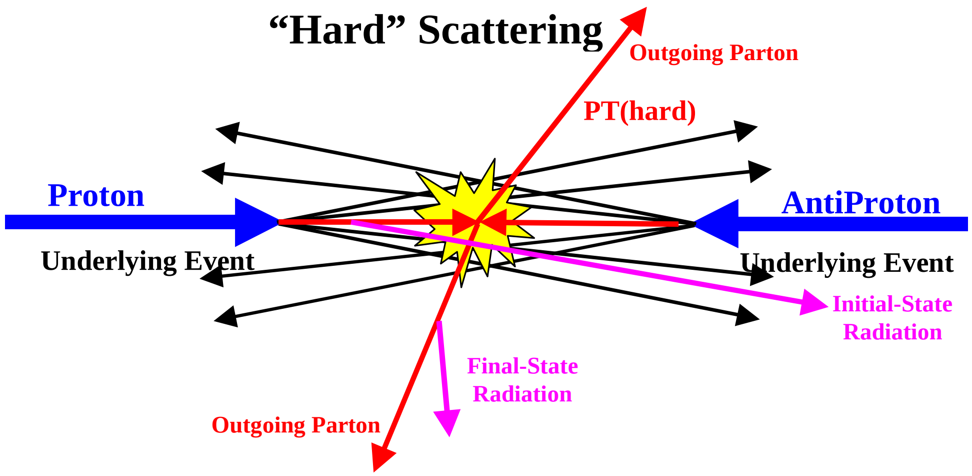
Rick Field
University of Florida
The CDF Collaboration

- Use the CDF "min-bias" data in conjunction with the CDF JET20 data to study the growth and development of "charged particle jets".
- Study a variety of "local" leading charged jet observables and compare with the QCD "hard" scattering Monte-Carlo models of Herwig, Isajet, and Pythia.
- Study a number of "global" observables, where to fit the observable the QCD Monte-Carlo models have to describe correctly the entire event structure. In particular, examine carefully the "underlying event" in hard-scattering processes.

Min-Bias + JET20 data

- Compare the "underlying event" in dijet versus Z-boson production.

“Hard” Proton-Antiproton Collisions

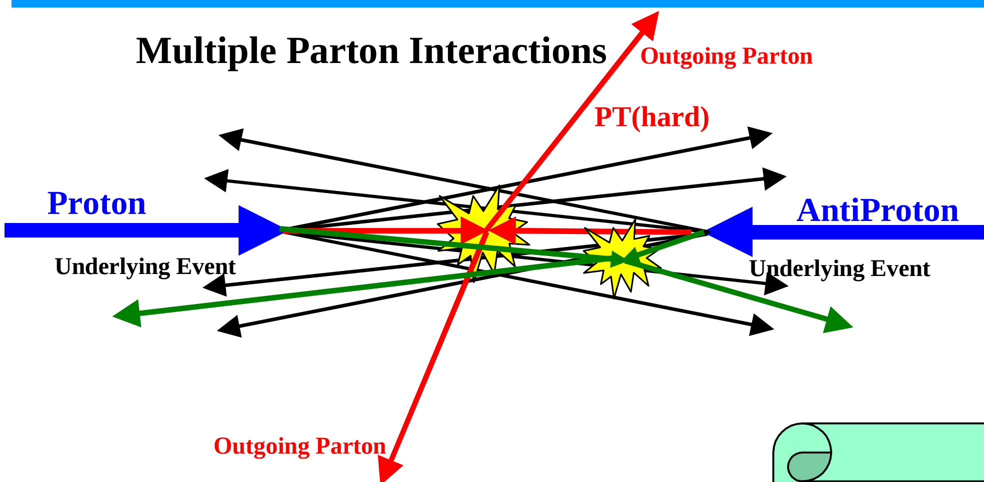


The “underlying event” consists of the beam-beam remnants and initial-state radiation

- **Illustration of a proton-antiproton collision in which a “hard” 2-to-2 parton scattering with transverse momentum, PT(hard), has occurred (take PT(hard) > 3 GeV).**
- **Isajet, Herwig, and Pythia are QCD “hard” scattering Monte-Carlo models.**

Isajet 7.32
Herwig 5.9
Pythia 6.115
Pythia 6.125
Pythia No MS

Multiple Parton Interactions



Pythia uses multiple parton interactions to enhace the underlying event.

- Pythia uses **multiple parton scattering** to enhance the underlying event; Isajet and Herwig do not.
- Isajet uses **independent fragmentation**; Herwig and Pythia do not.
- Herwig and Pythia modify the leading-log picture to include "color coherence effects" which leads to **"angle ordering"** within the parton shower; Isajet does not.

Isajet 7.32
Herwig 5.9
Pythia 6.115
Pythia 6.125
Pythia No MS

Pythia 6.115 and 6.125 differ in the amount of multiple parton interactions.

No multiple parton interactions.

Comparing Data with QCD Monte-Carlo Models

Charged Particle Data

Select "clean" region

- Zero or one vertex
- |zc-zv| < 2 cm, |CTC d0| < 1 cm
- Require PT > 0.5 GeV, |η| < 1
- Assume a uniform track finding efficiency of 92%
- Errors include both statistical and correlated systematic uncertainties

Uncorrected data

WYSIWYG

What you see is what you get.

Almost!

Look only at the charged particles measured by the CTC.

compare

QCD Monte-Carlo

Make efficiency corrections

- Require PT > 0.5 GeV, |η| < 1
- Make an 8% correction for the track finding efficiency
- Errors (statistical plus systematic) of around 5%

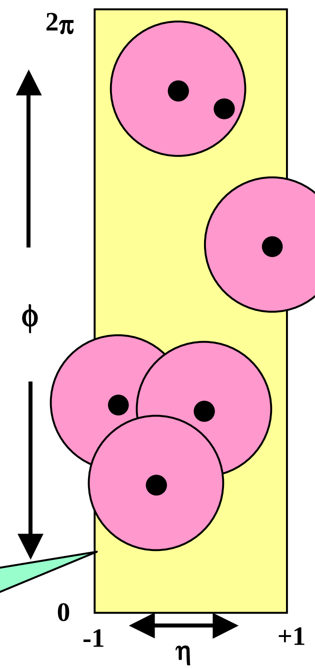
Corrected theory

Small Corrections!

Define "Charged Jets" as Circular Regions in η-ϕ Space

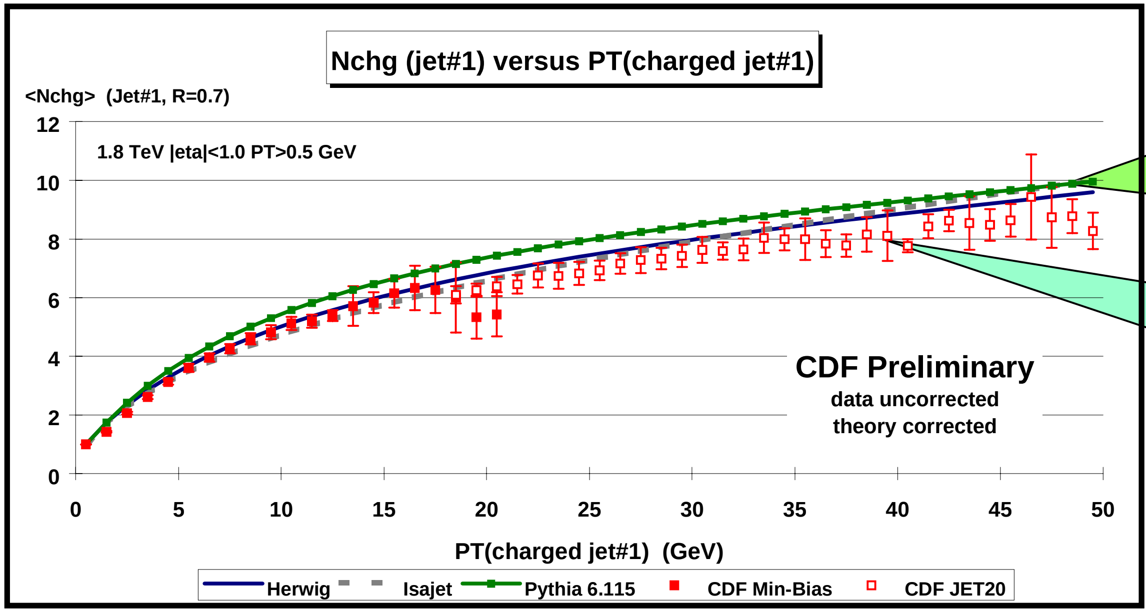
- **Order Charged Particles in P_T ($|\eta| < 1$ $P_T > 0.5$ GeV).**
- **Start with highest P_T particle and include in the "jet" all particles ($|\eta| < 1$ $P_T > 0.5$ GeV) within radius R = 0.7.**
- **Go to next highest P_T particle (not already included in a previous jet) and include in the "jet" all particles ($|\eta| < 1$ $P_T > 0.5$ GeV) within radius R = 0.7 (not already included in a previous jet).**
- **Continue until all particles are in a "jet".**
- **Maximum number of "jet" is about $2(2)(2\pi)/(\pi(0.7)^2)$ or 16.**

"Charged Jets" contain particles from the underlying event in addition to particles from the outgoing partons.



6 particles
5 "jets"

The Evolution of "Charged Jets" from 0.5 to 50 GeV



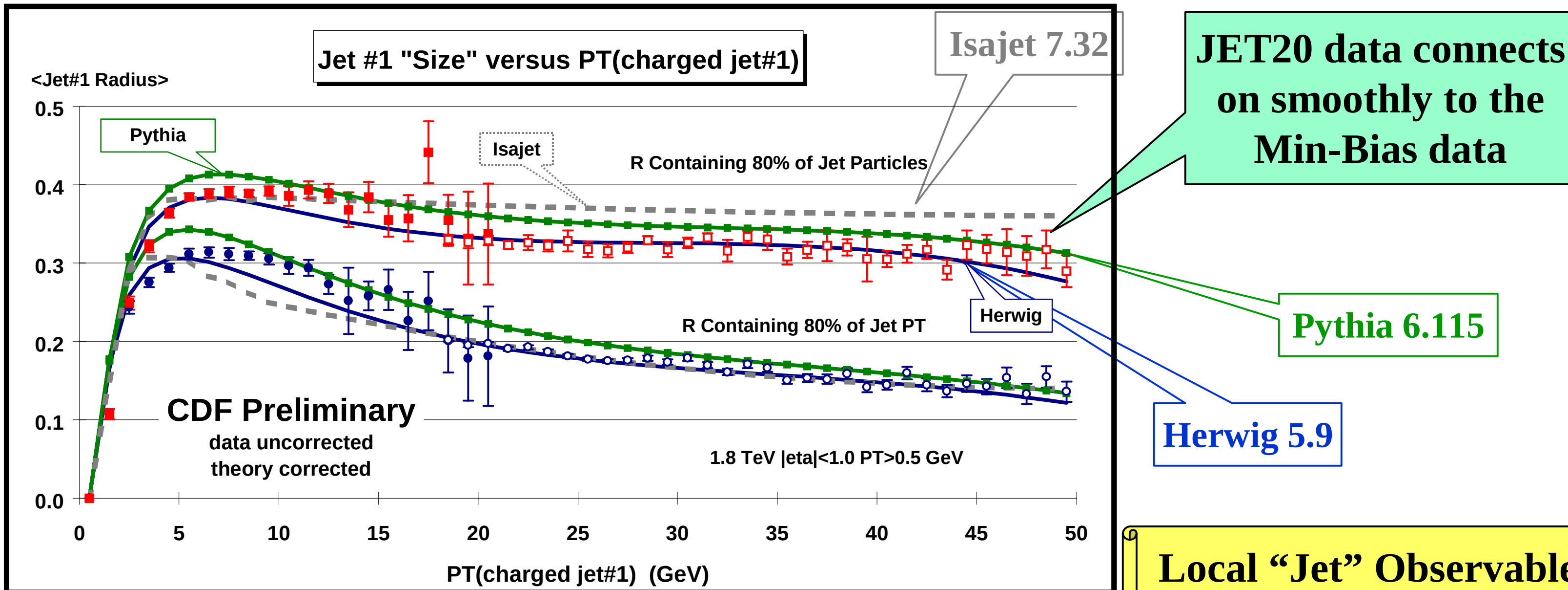
QCD "hard" scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115

JET20 data connects on smoothly to the Min-Bias data

Local "Jet" Observable

- **Compares data on the average number of charged particles within Jet#1 (leading jet, R = 0.7) with the QCD "hard" scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115.**
- **Use the JET20 data to extend the range to 0.5 < PT(chgjet#1) < 50 GeV. Plot shows <Nchg(jet#1)> versus PT(chgjet#1).**
- **Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo predictions have been corrected for efficiency.**

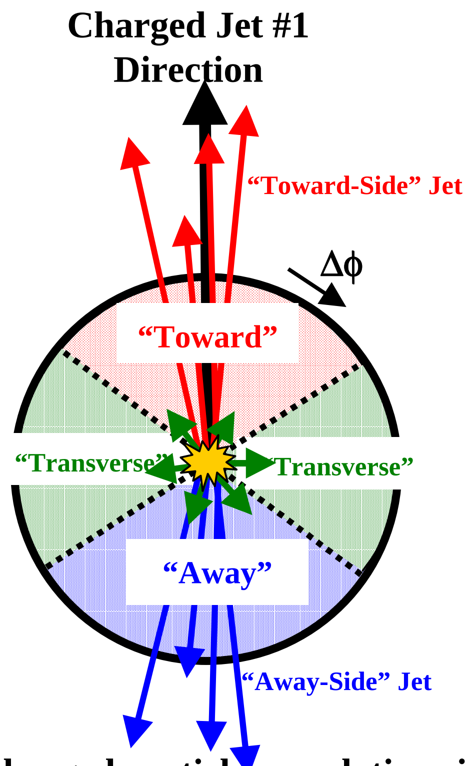
Jet#1 “Size” vs PT(chgjet#1)

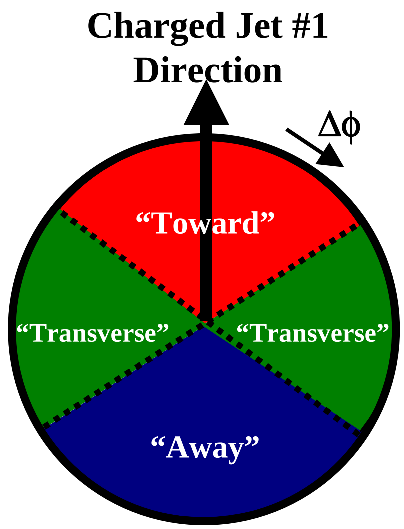


Local “Jet” Observable

- **Compares data on the average radius containing 80% of the charged particles and 80% of the charged PTsum of jet#1 (leading charged jet) with the QCD “hard” scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115.**
- **Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo predictions have been corrected for efficiency.**

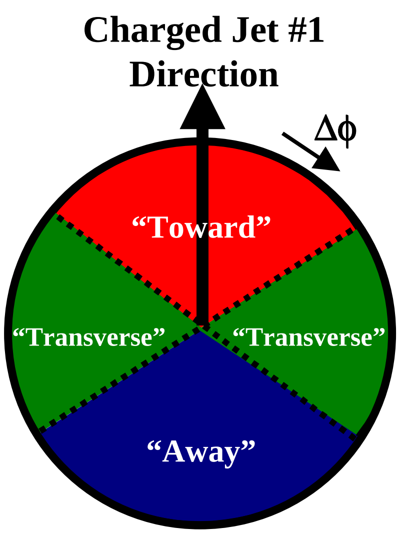
Charged Particle Δϕ Correlations

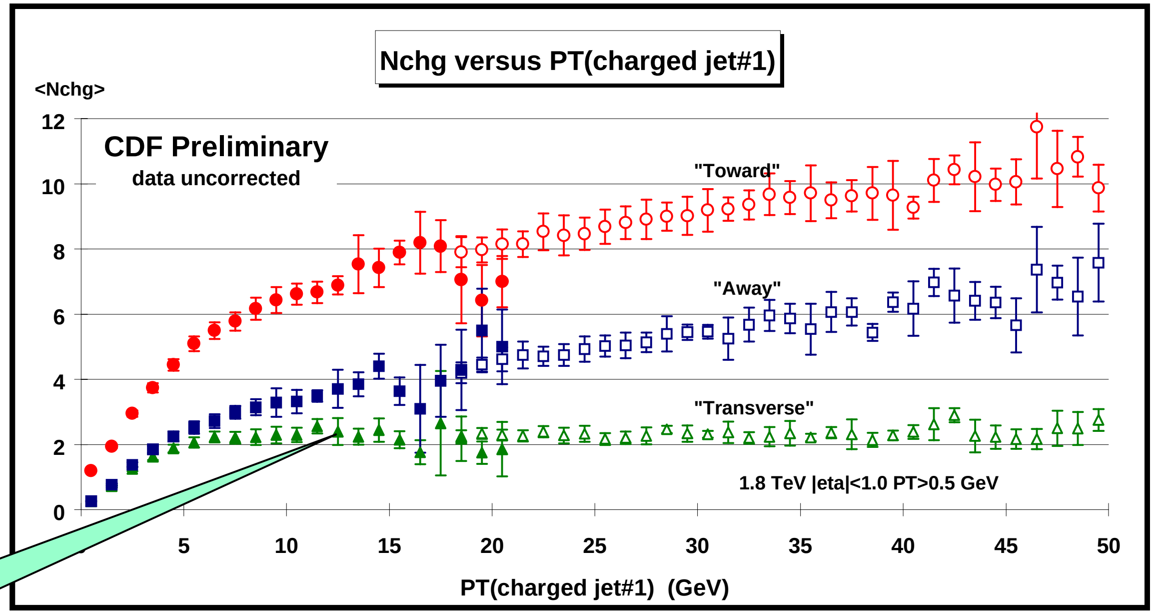




- **Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading charged particle jet.**
- **Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".**
- **All three regions have the same size in η-ϕ space, $\Delta\eta x\Delta\phi = 2x120^o$.**

DiJet: Charged Multiplicity versus PT(chgjet#1)



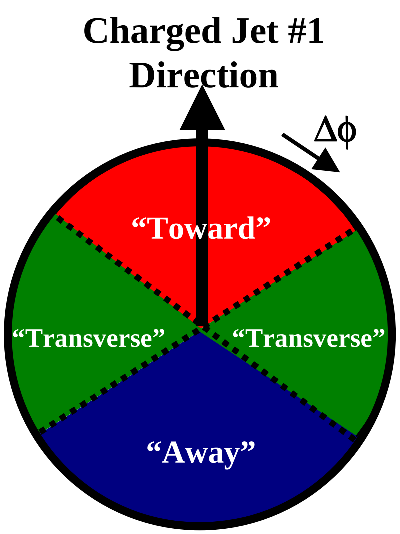


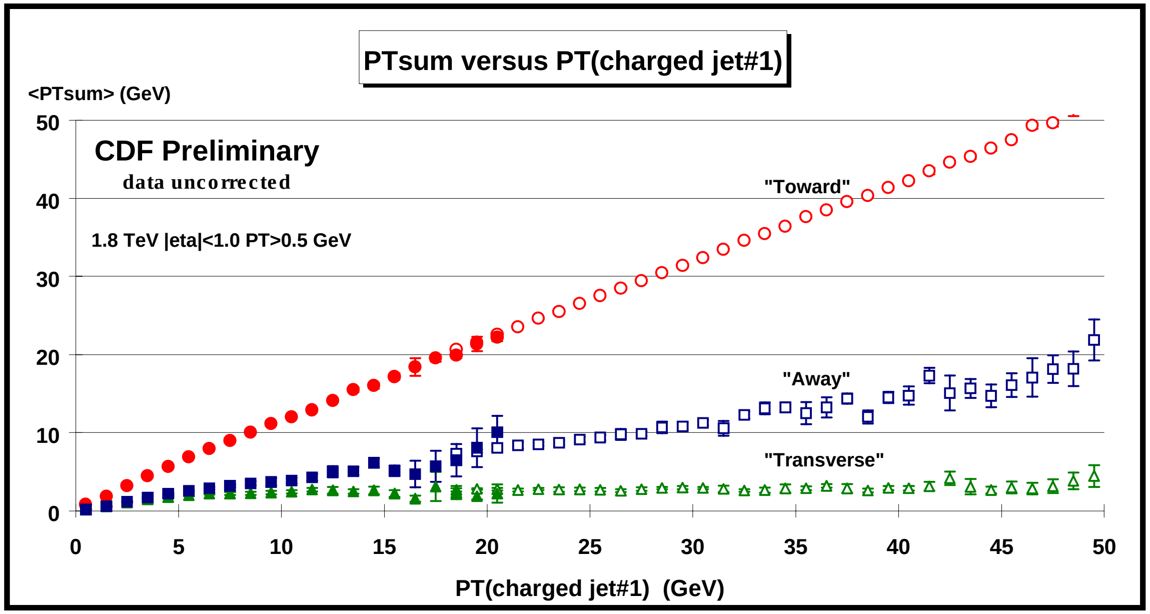
Underlying event “plateau”

Refer to the Min-Bias + JET20 data as the “dijet” data.

- **Dijet data on the average number of “toward” (|Δϕ|<60º), “transverse” (60<|Δϕ|<120º), and “away” (|Δϕ|>120º) charged particles (P_T > 0.5 GeV, |η| < 1, including jet#1) as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the <Nchg> in a 1 GeV bin. The solid (open) points are the Min-Bias (JET20) data. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.**

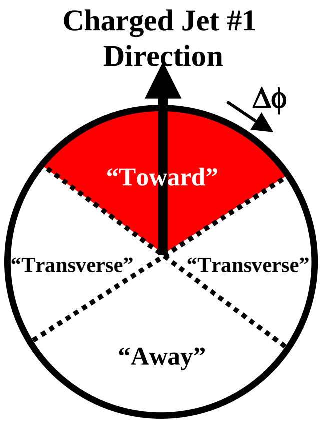
DiJet: Charged PTsum versus PT(chgjet#1)

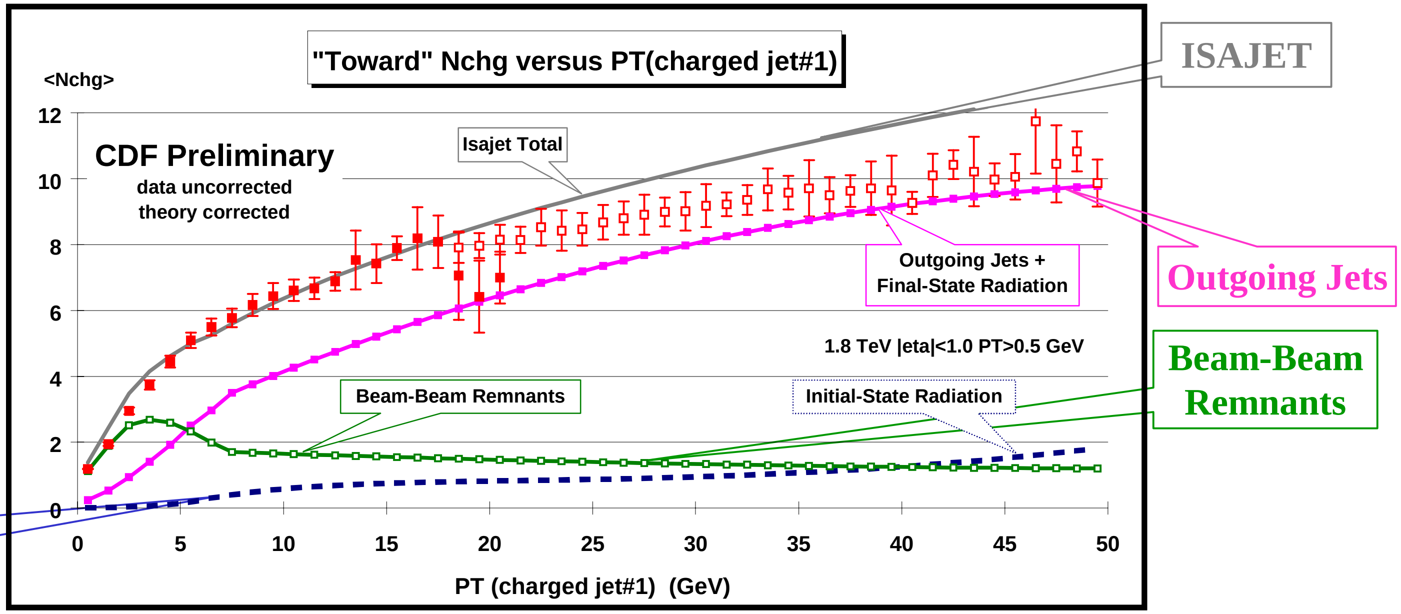




- **Dijet data** on the average scalar P_T sum of **“toward” ($|\Delta\phi|<60^o$)**, **“transverse” ($60<|\Delta\phi|<120^o$)**, and **“away” ($|\Delta\phi|>120^o$)** charged particles ($P_T > 0.5$ GeV, $|\eta| < 1$, including jet#1) as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the <PTsum> in a 1 GeV bin. The solid (open) points are the Min-Bias (JET20) data. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.

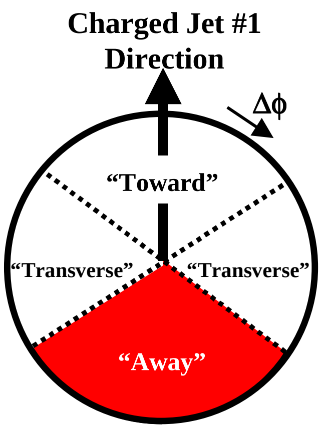
DiJet: "Toward" Nchg versus PT(chgjet#1)

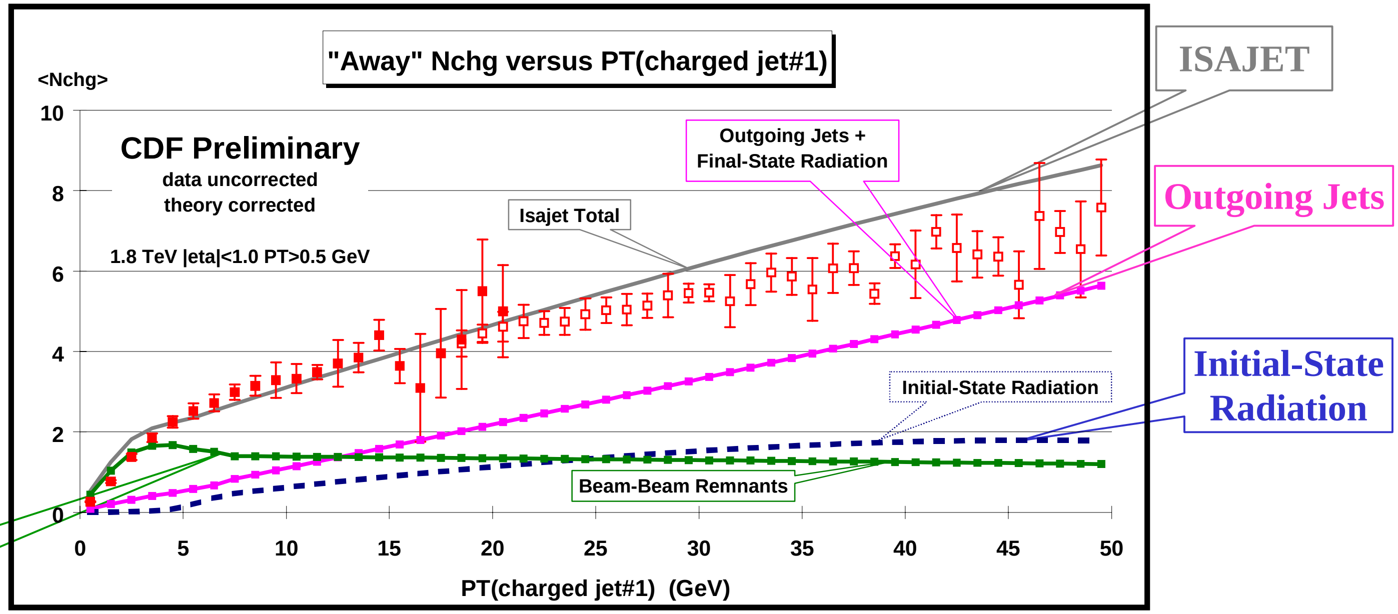




- **Plot shows the dijet "toward" <Nchg> vs P_T(chgjet#1) compared to the QCD "hard" scattering predictions of ISAJET 7.32.**
- **The predictions of ISAJET are divided into three categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants), charged particles that arise from initial-state radiation, and charged particles that result from the outgoing jets plus final-state radiation.**

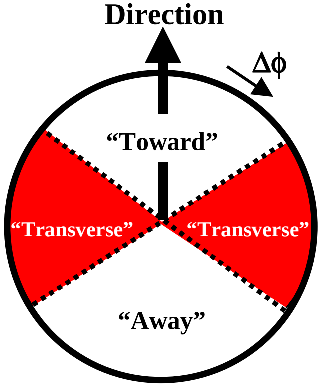
DiJet: "Away" Nchg versus PT(chgjet#1)

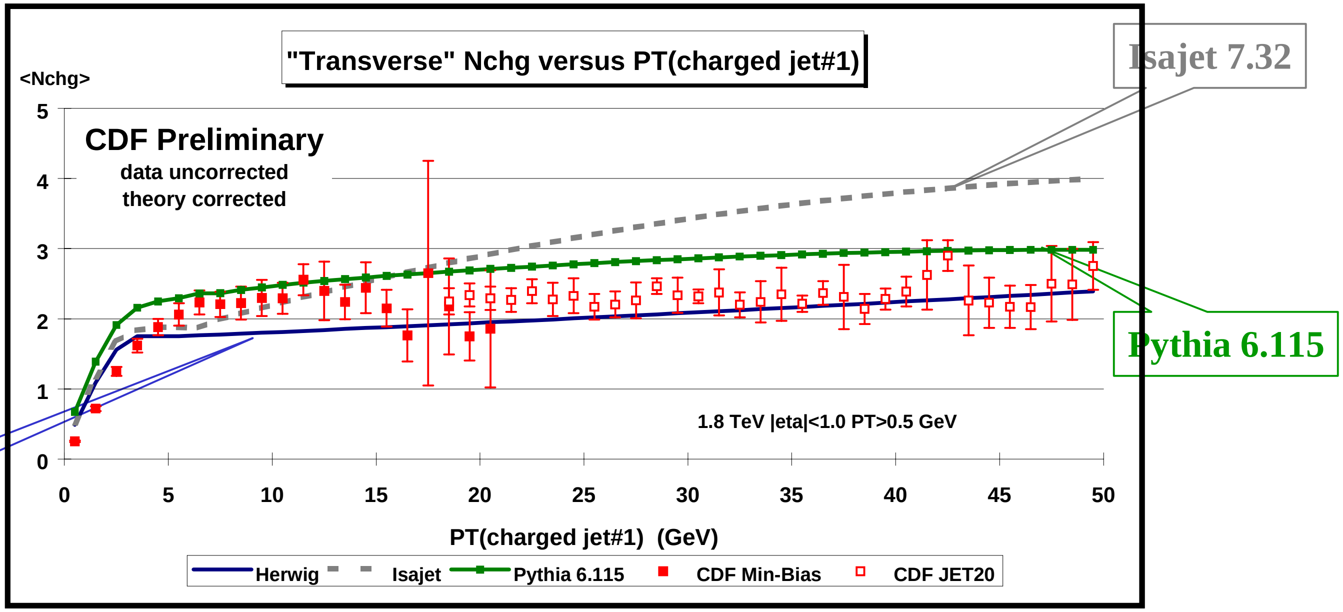




- Plot shows the dijet "away" <Nchg> vs P_T(chgjet#1) compared to the QCD "hard" scattering predictions of ISAJET 7.32.
- The predictions of ISAJET are divided into three categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants), charged particles that arise from initial-state radiation, and charged particles that result from the outgoing jets plus final-state radiation .

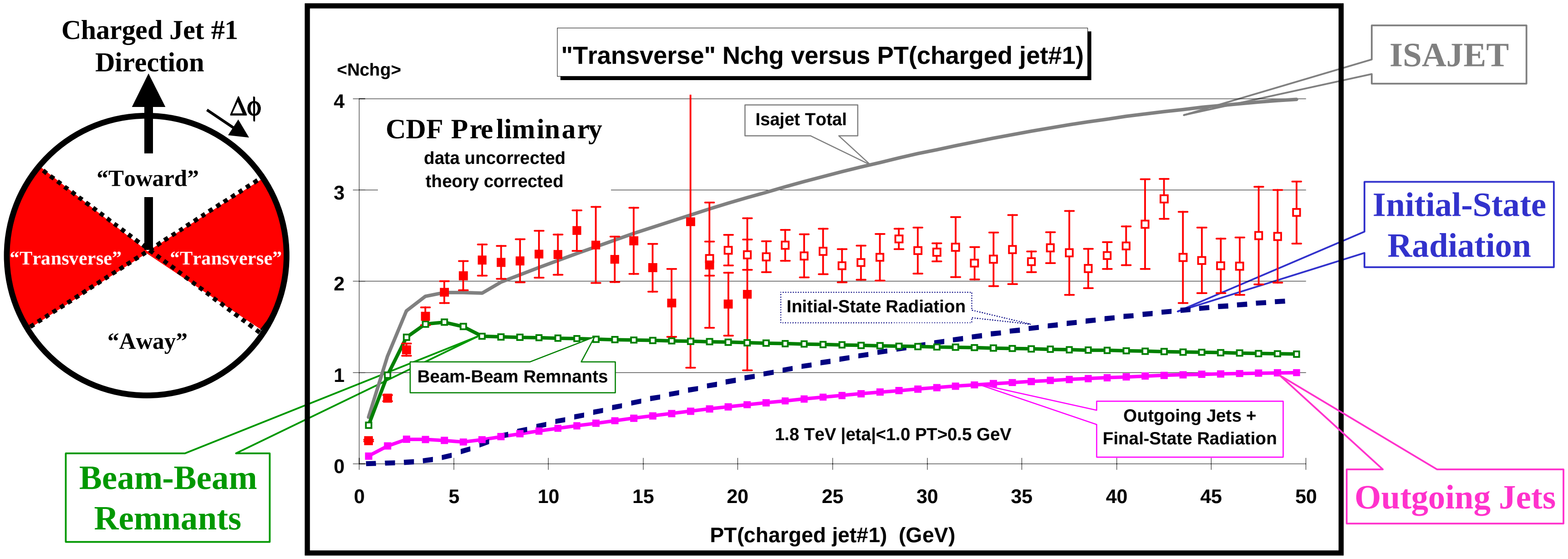
DiJet: "Transverse" Nchg versus PT(chgjet#1)





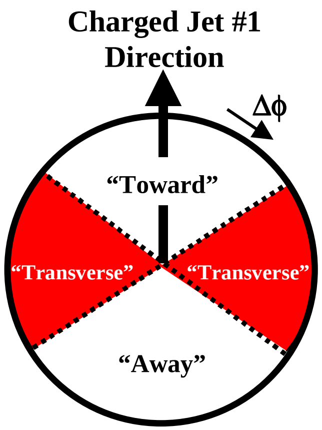
- Plot shows **"Transverse" <Nchg> in the vs PT(chgjet#1)** compared to the QCD "hard" scattering predictions of **Herwig 5.9**, **Isajet 7.32**, and **Pythia 6.115**.
- Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo predictions have been corrected for efficiency.

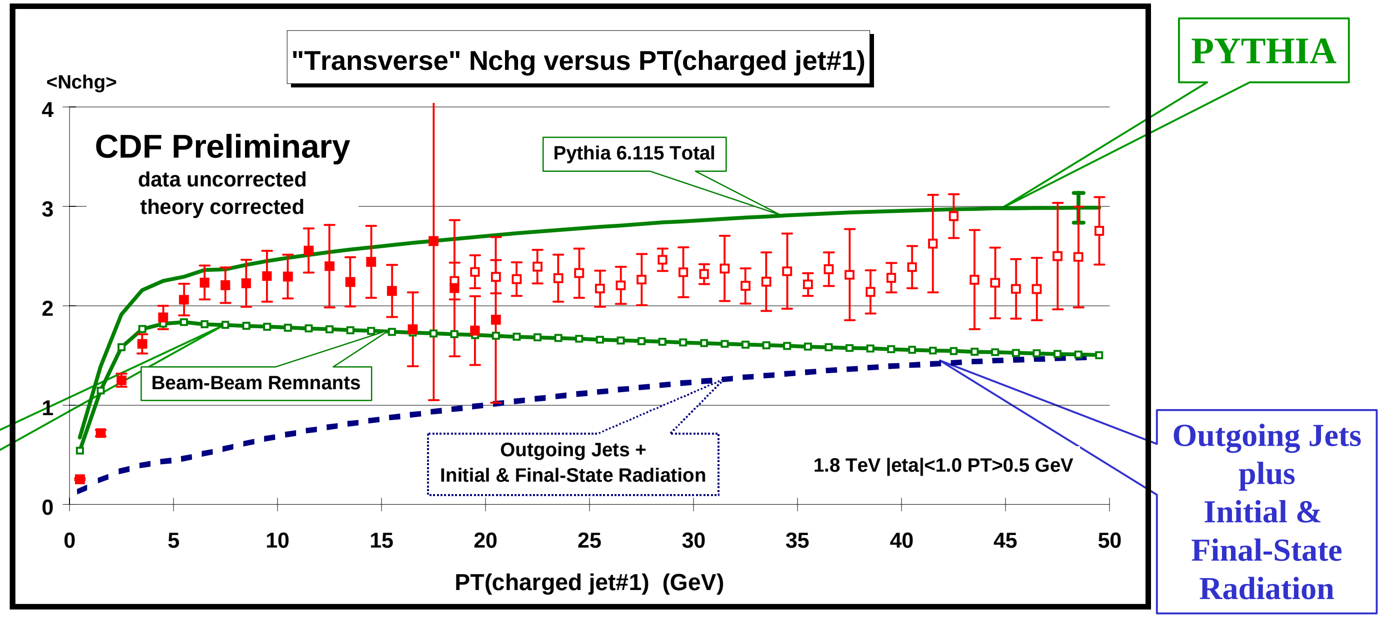
DiJet: “Transverse” Nchg versus PT(chgjet#1)



- Plot shows the dijet “transverse” <Nchg> vs P_T(chgjet#1) compared to the QCD “hard” scattering predictions of ISAJET 7.32.
- The predictions of ISAJET are divided into three categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants), charged particles that arise from initial-state radiation, and charged particles that result from the outgoing jets plus final-state radiation.

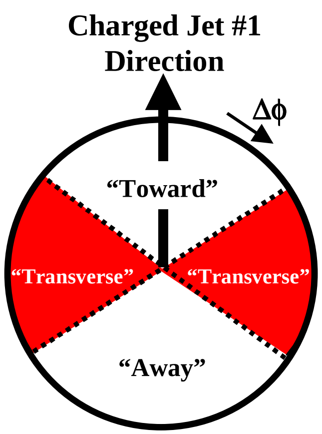
DiJet: "Transverse" Nchg versus PT(chgjet#1)

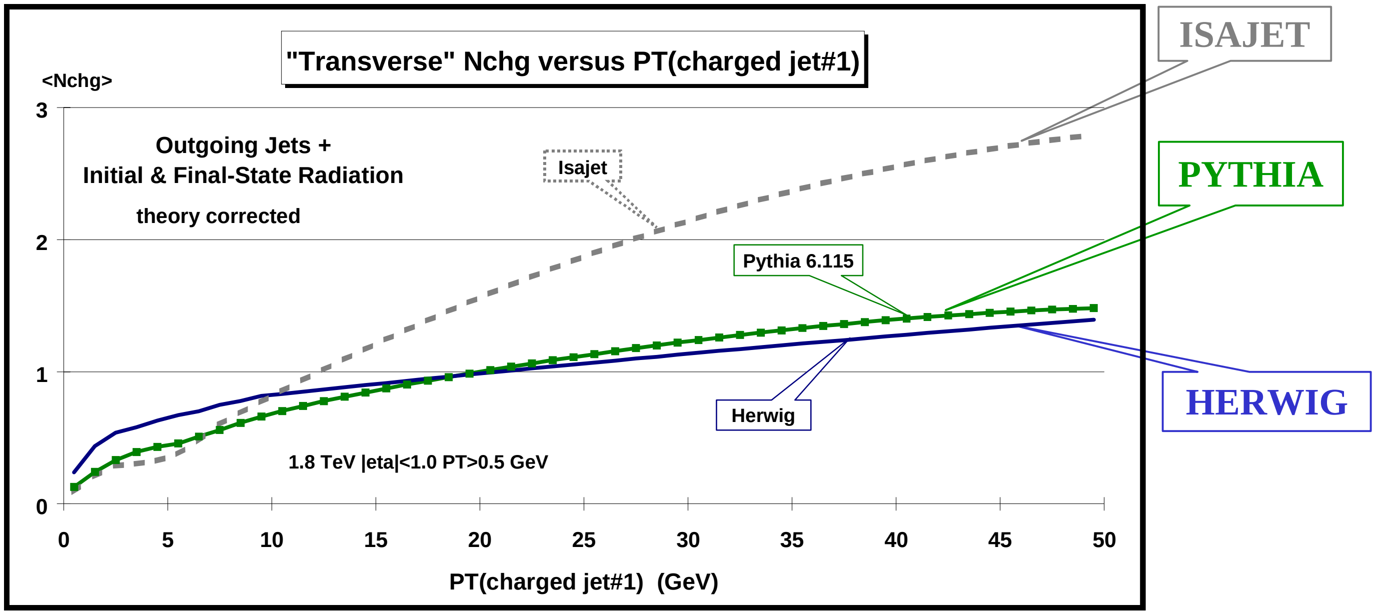




- **Plot shows the dijet "transverse" <Nchg> vs P_T(chgjet#1) compared to the QCD "hard" scattering predictions of PYTHIA 6.115.**
- **The predictions of PYTHIA are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).**

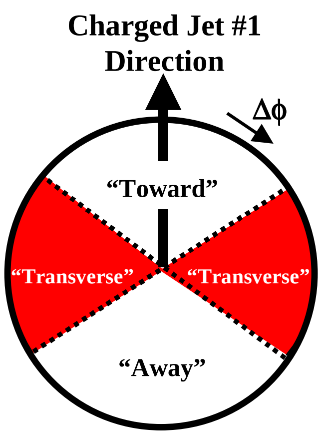
DiJet: "Transverse" Nchg versus PT(chgjet#1)

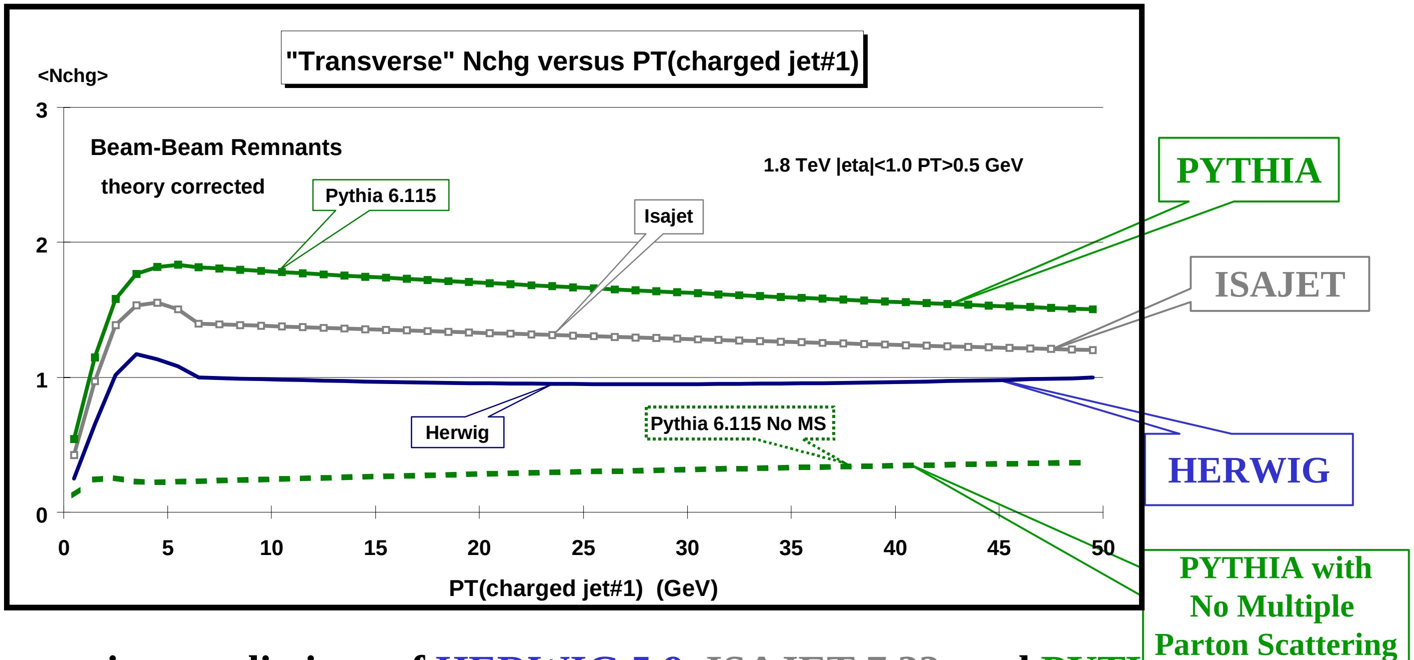




- QCD "hard" scattering predictions of HERWIG 5.9, ISAJET 7.32, and PYTHIA 6.115.
- Plot shows the dijet "transverse" <Nchg> vs P_T(chgjet#1) arising from the outgoing jets plus initial and finial-state radiation (hard scattering component).
- HERWIG and PYTHIA modify the leading-log picture to include "color coherence effects" which leads to "angle ordering" within the parton shower. Angle ordering produces less high P_T radiation within a parton shower.

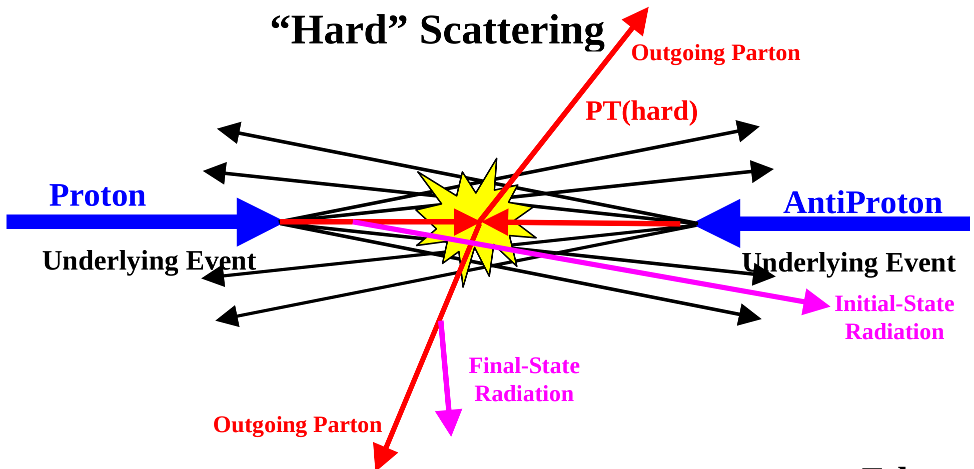
DiJet: “Transverse” Nchg versus PT(chgjet#1)





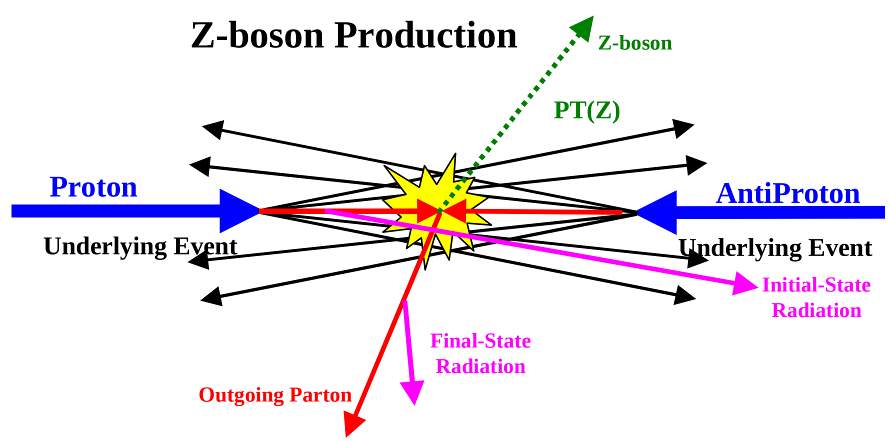
- QCD “hard” scattering predictions of HERWIG 5.9, ISAJET 7.32, and PYTHIA 6.115.
- Plot shows the dijet “transverse” <Nchg> vs P_T(chgjet#1) arising from the beam-beam remnants. For Pythia the beam-beam remnants include contributions from multiple parton scattering.
- Since we only include charged particles with $P_T > 0.5$ GeV, the <Nchg> seen above is related to the P_T distribution of the beam-beam remnants compoment.

The Underlying Event: DiJet vs Z-Jet

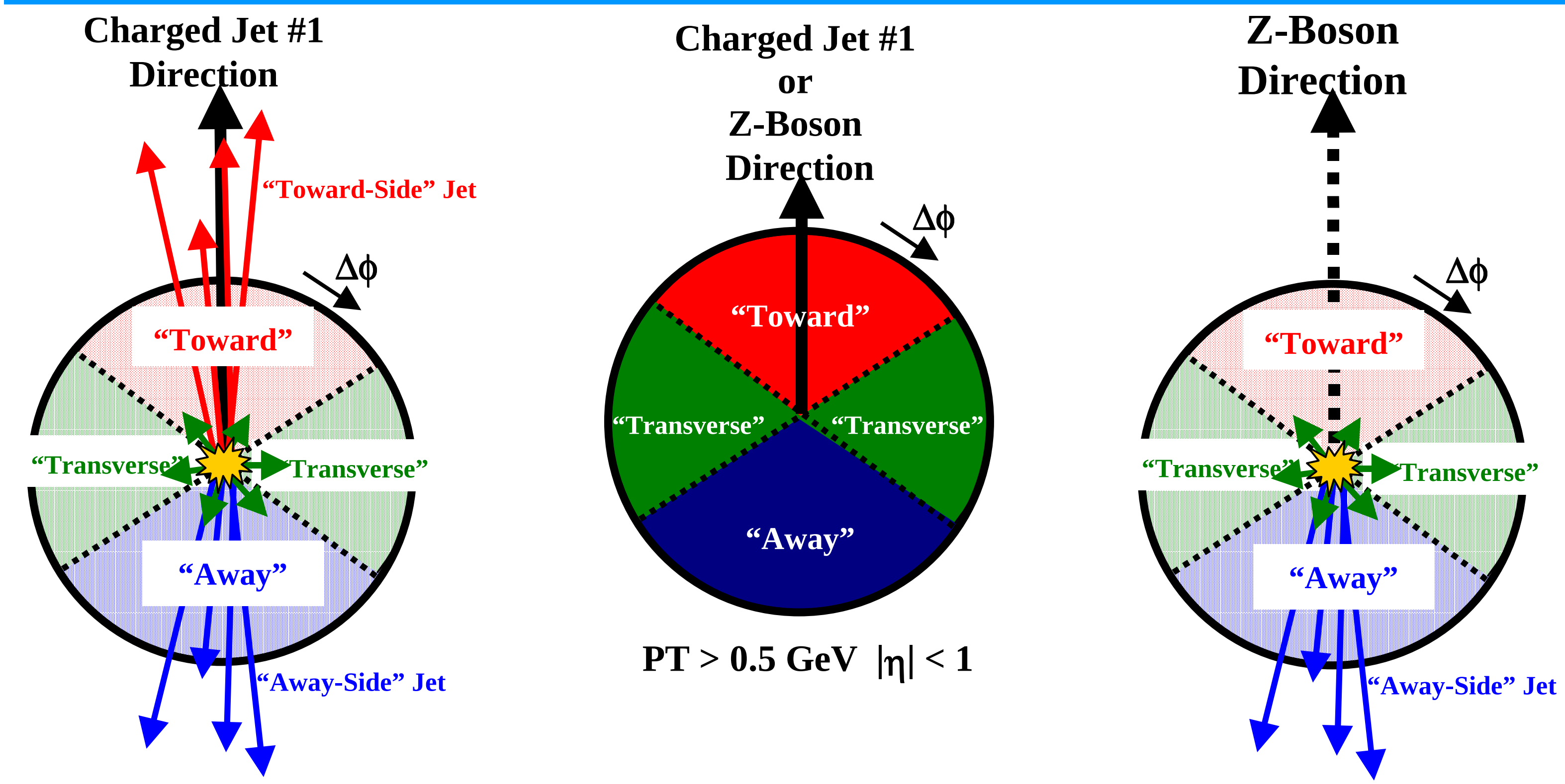


Refer to
Min-Bias +JET20
as
DiJet Data

The “underlying event” consists of the beam-beam remnants and initial-state radiation

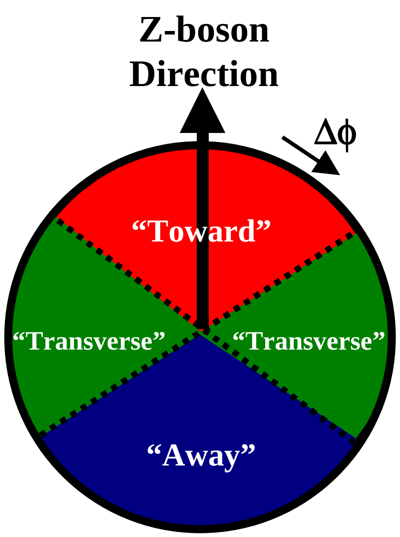


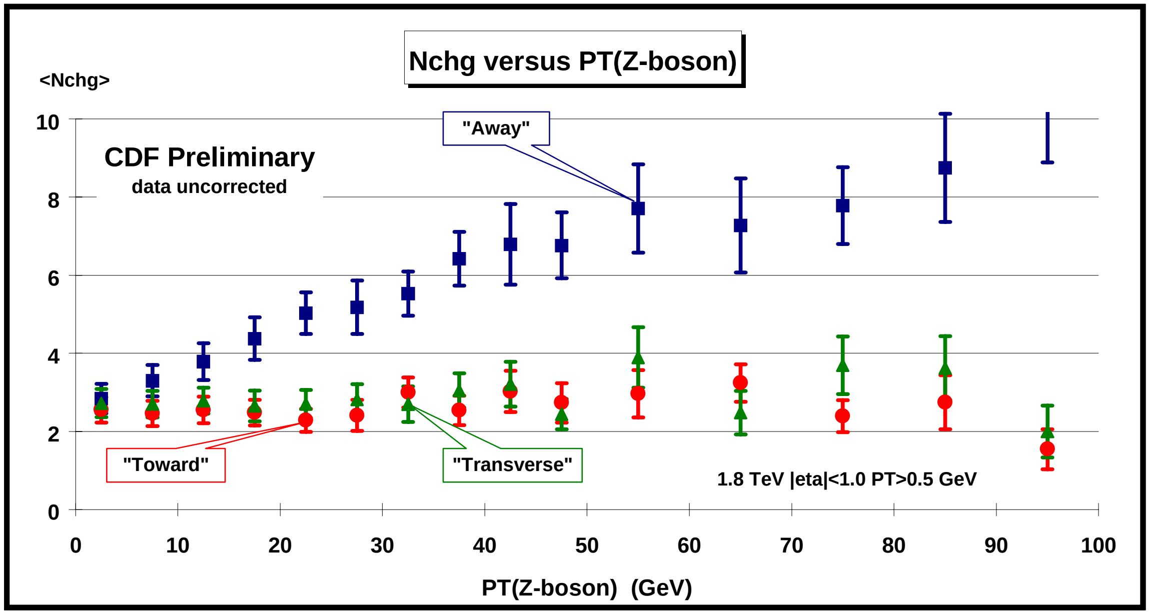
Charged Particle Δϕ Correlations



- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading charged particle jet or the Z-boson.
- Define $|\Delta\phi| < 60^{o}$ as "Toward", $60^{o} < |\Delta\phi| < 120^{o}$ as "Transverse", and $|\Delta\phi| > 120^{o}$ as "Away".
- All three regions have the same size in η-ϕ space, $\Delta\eta \times \Delta\phi = 2 \times 120^{o}$.

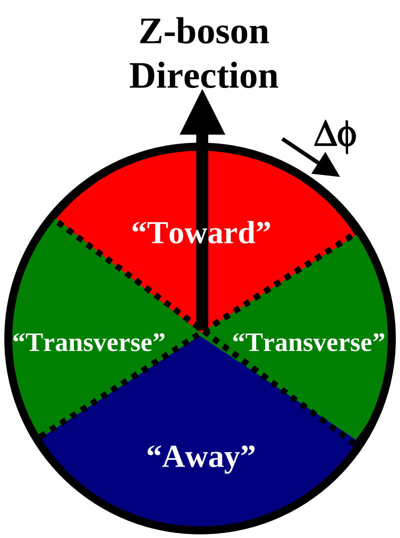
Z-boson: Charged Multiplicity versus PT(Z)

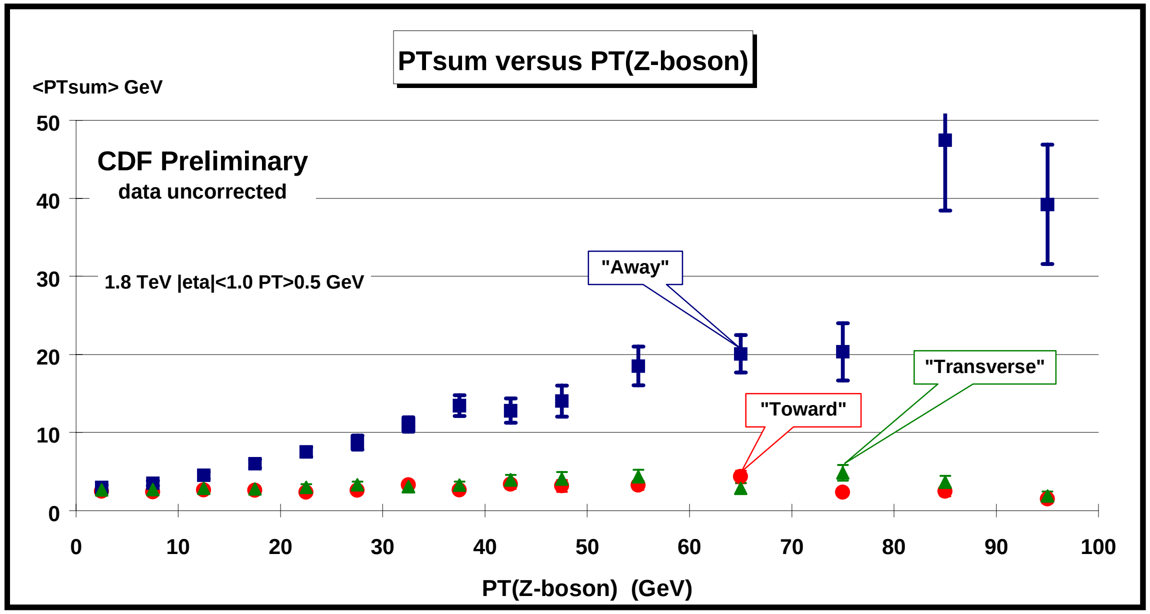




⇨ **Z-boson data on the average number of “toward” (|Δφ|<60º), “transverse” (60<|Δφ|<120º), and “away” (|Δφ|>120º) charged particles (P_T > 0.5 GeV, |η| < 1, excluding decay products of the Z-boson) as a function of the transverse momentum of the Z-boson. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.**

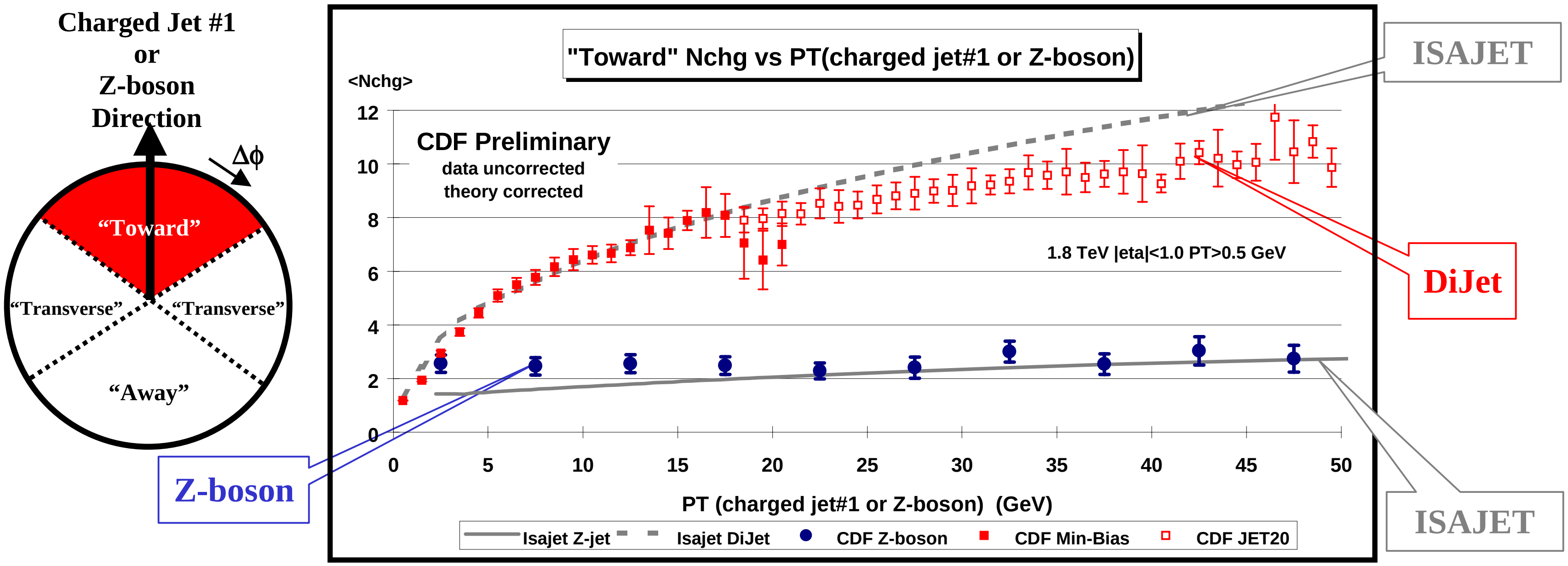
Z-boson: Charged PTsum versus PT(Z)





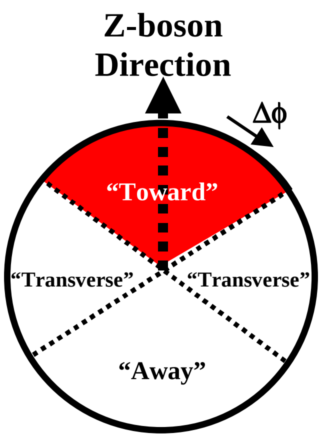
⇨ **Z-boson data on the average *scalar* P_T sum of "toward" ($|\Delta\phi|<60^o$), "transverse" ($60<|\Delta\phi|<120^o$), and "away" ($|\Delta\phi|>120^o$) charged particles (P_T > 0.5 GeV, $|\eta|$ < 1, excluding decay products of the Z-boson) as a function of the transverse momentum of the Z-boson. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.**

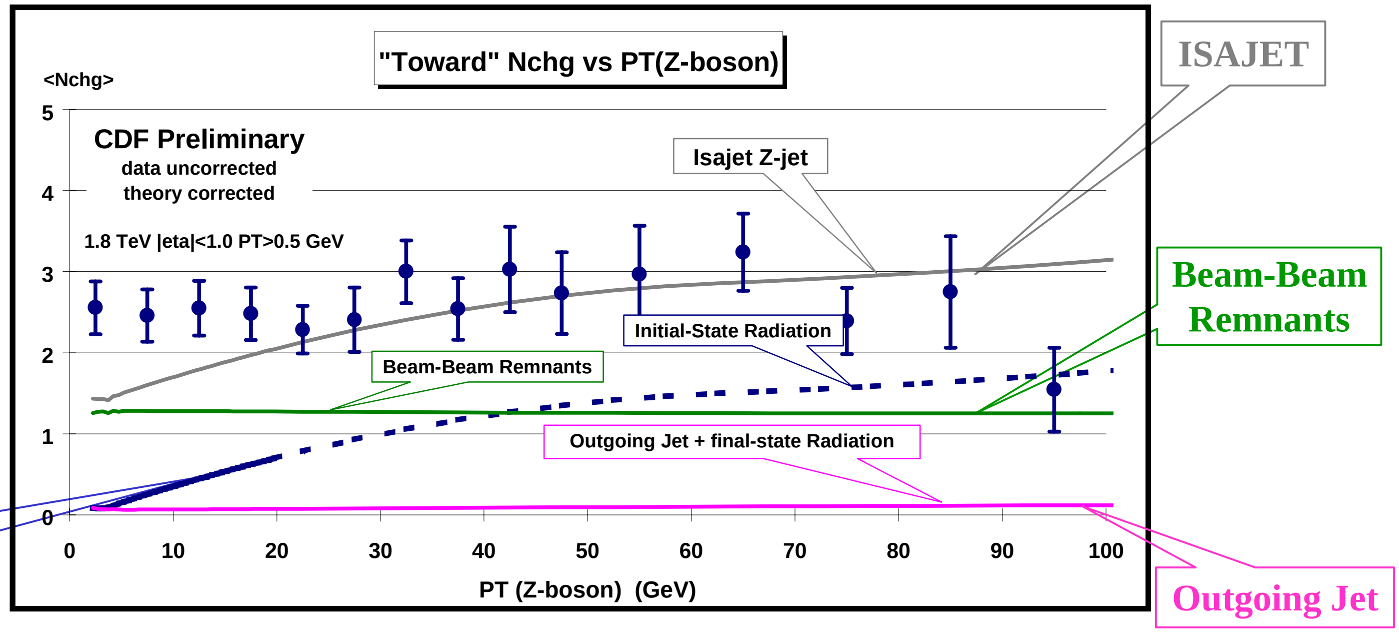
DiJet vs Z-Jet
"Toward" Nchg



- ⇨ **Comparison of the dijet and the Z-boson data on the average number of charged particles (P_T > 0.5 GeV, |η| <1) for the "toward" region.**
- ⇨ **The plot shows the QCD Monte-Carlo predictions of ISAJET 7.32 for dijet (dashed) and "Z-jet" (solid) production.**

Z-boson: “Toward” Nchg versus PT(Z)

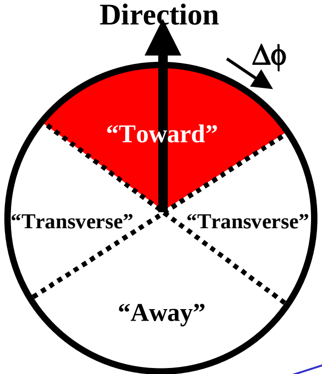


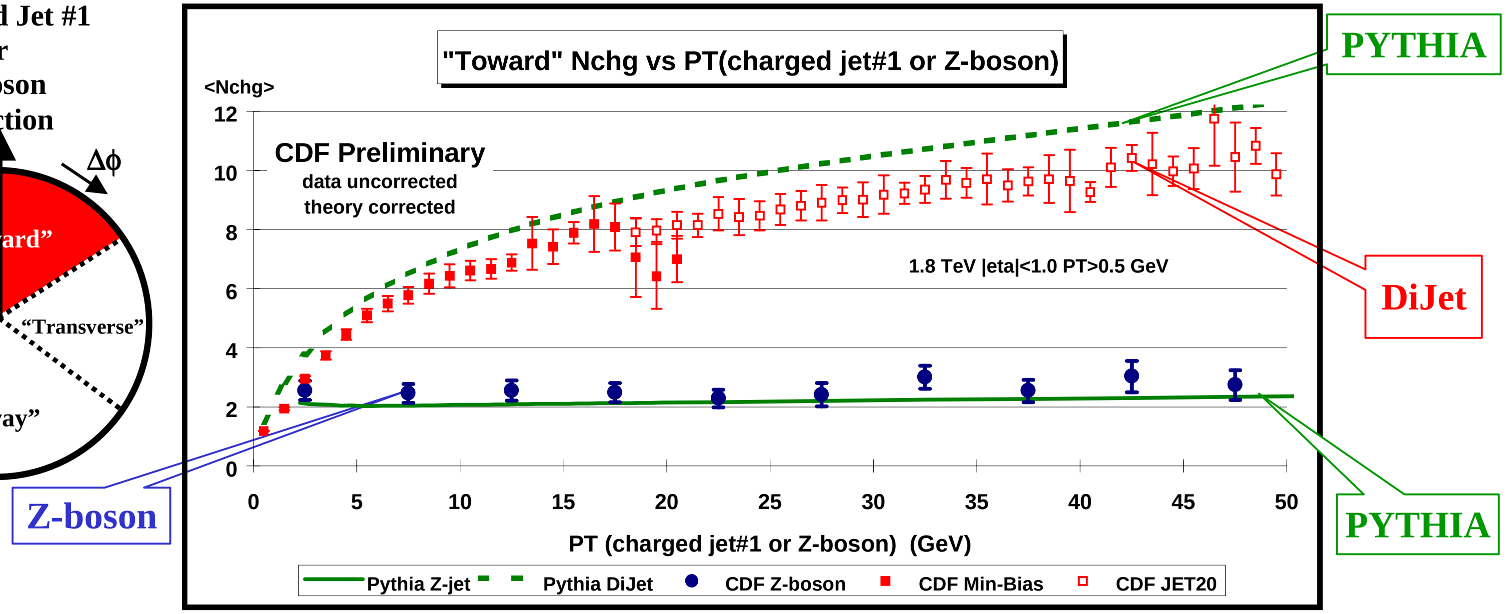


- Plot shows the Z-boson **“toward” <Nchg> vs P_T(Z)** compared to the “Z+jet” QCD Monte-Carlo predictions of **ISAJET 7.32**.
- The predictions of ISAJET are divided into three categories: charged particles that arise from the break-up of the beam and target (**beam-beam remnants**), charged particles that arise from **initial-state radiation**, and charged particles that result from the **outgoing jet plus final-state radiation** .

DiJet vs Z-Jet “Toward” Nchg

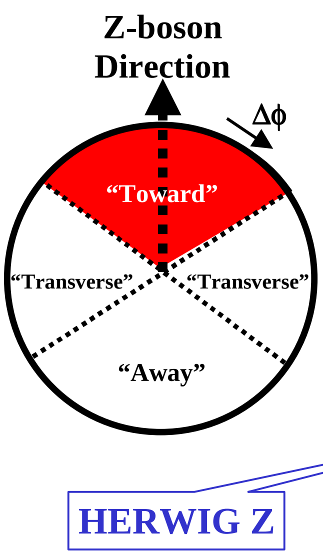
Charged Jet #1 or Z-boson Direction

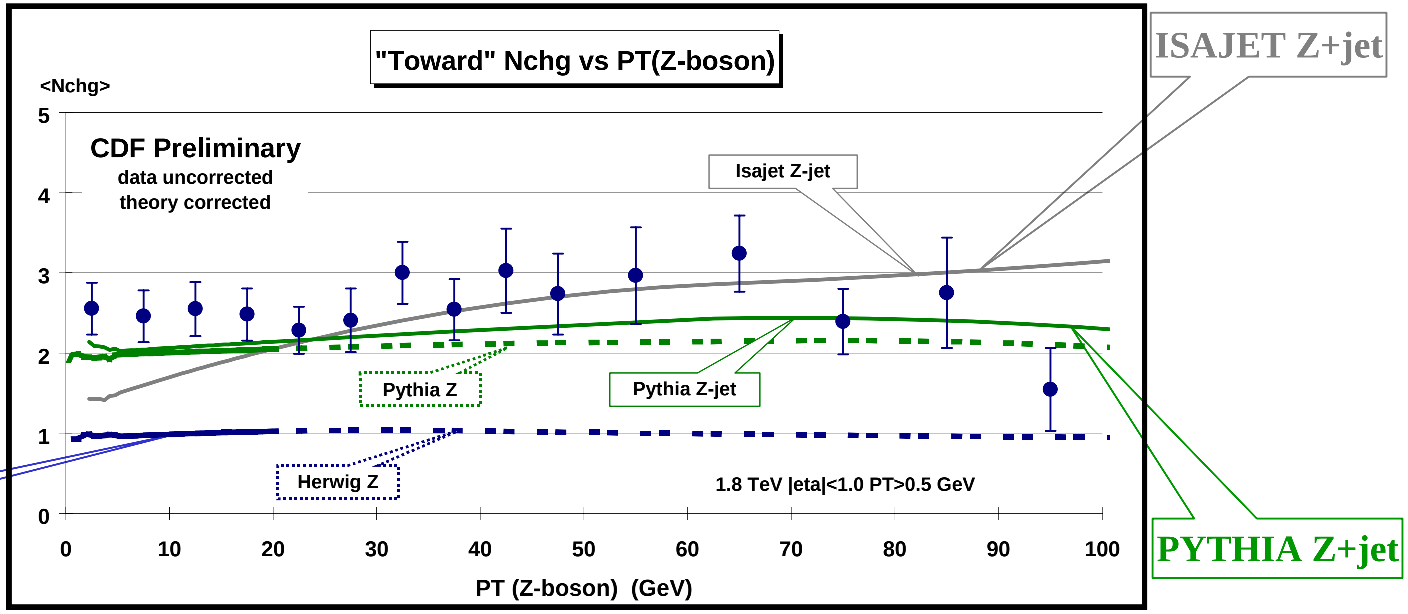




- Comparison of the dijet and the Z-boson data on the average number of charged particles ($P_T > 0.5$ GeV, $|\eta| < 1$) for the “toward” region.
- The plot shows the QCD Monte-Carlo predictions of PYTHIA 6.115 for dijet (dashed) and “Z-jet” (solid) production.

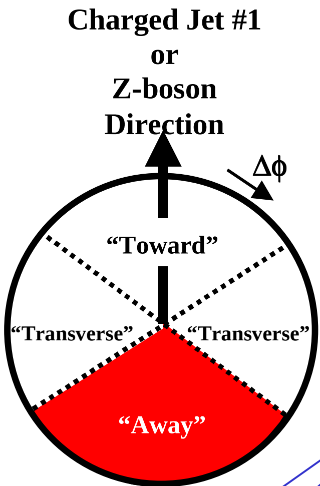
Z-boson: "Toward" Nchg versus PT(Z)

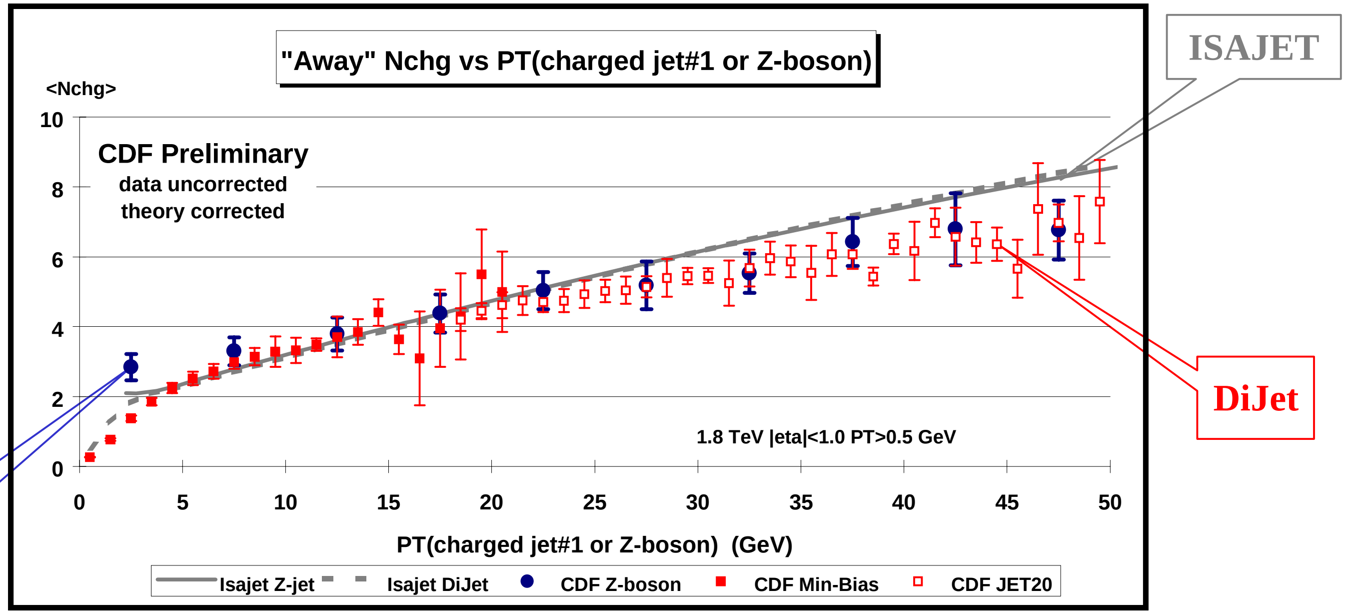




⇨ **Z-boson data on the average number of charged particles (P_T > 0.5 GeV and |η| < 1) as a function of P_T(Z) for the "toward" region compared with the QCD Monte-Carlo predictions of HERWIG 5.9 ("Z"), ISAJET 7.32 ("Z-jet"), and PYTHIA 6.115 ("Z", "Z-jet").**

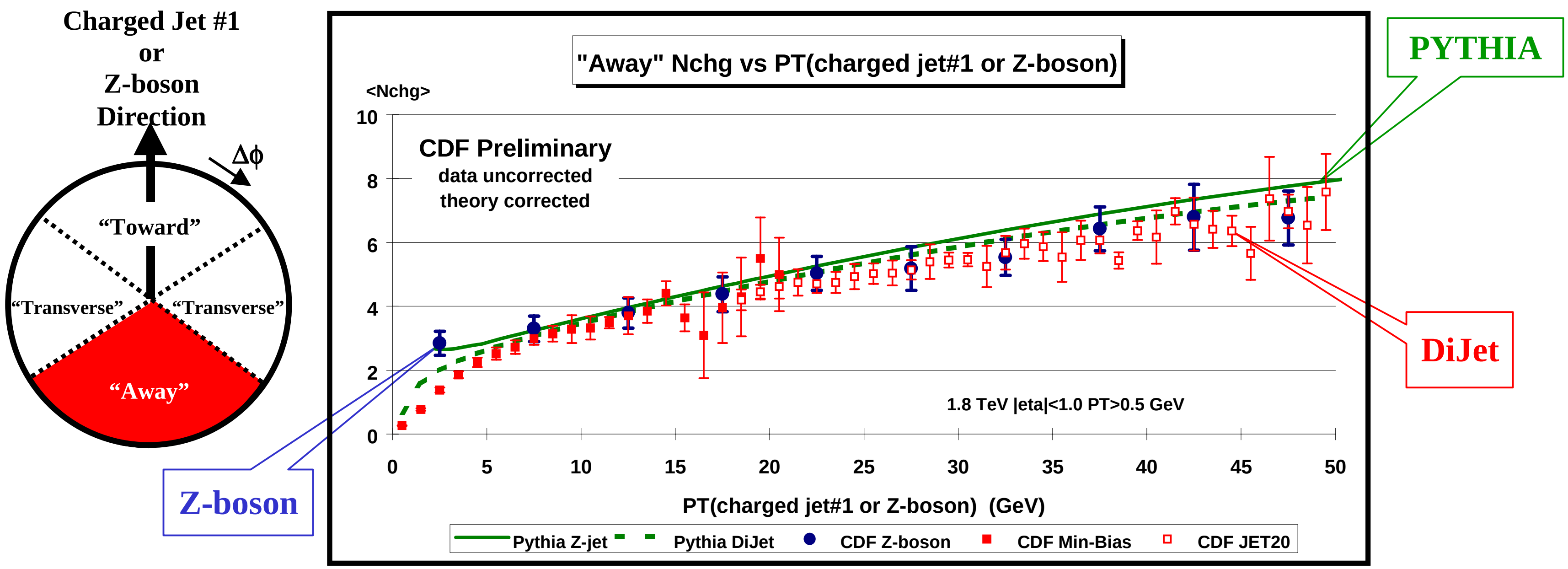
DiJet vs Z-Jet
“Away” Nchg





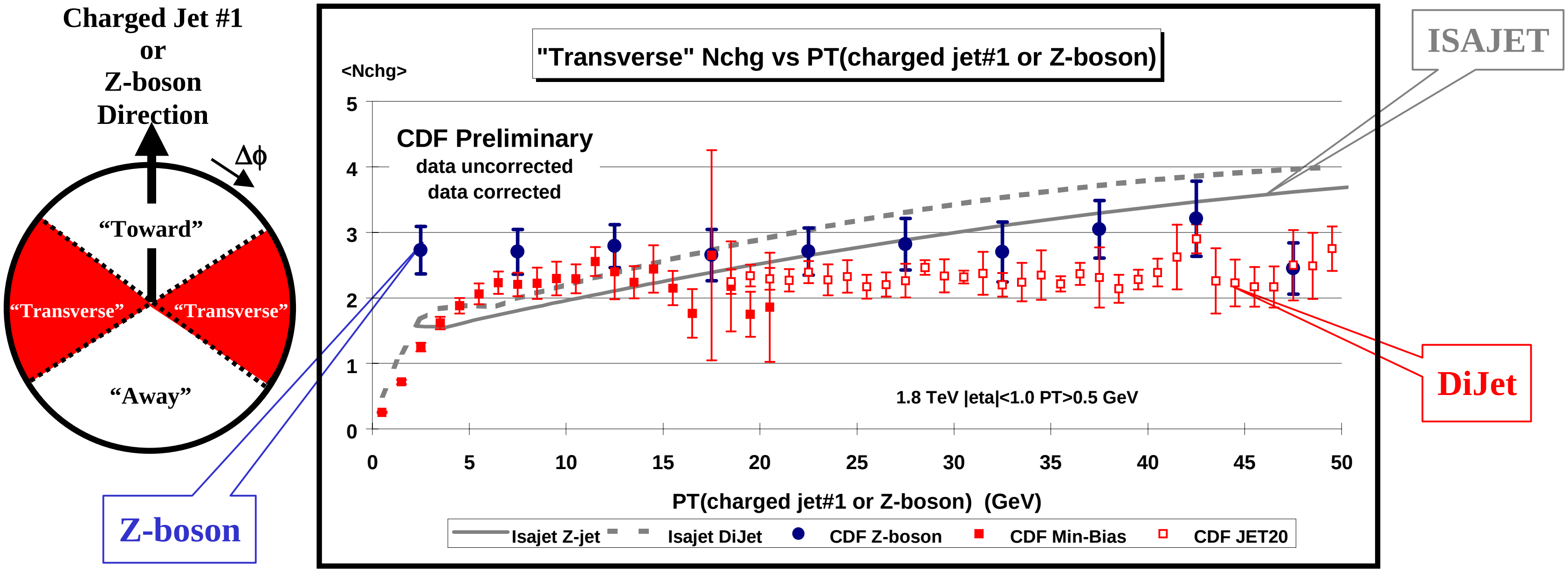
- Comparison of the dijet and the Z-boson data on the average number of charged particles ($P_T > 0.5$ GeV, $|\eta| < 1$) for the “away” region.
- The plot shows the QCD Monte-Carlo predictions of ISAJET 7.32 for dijet (dashed) and “Z-jet” (solid) production.

DiJet vs Z-Jet
“Away” Nchg



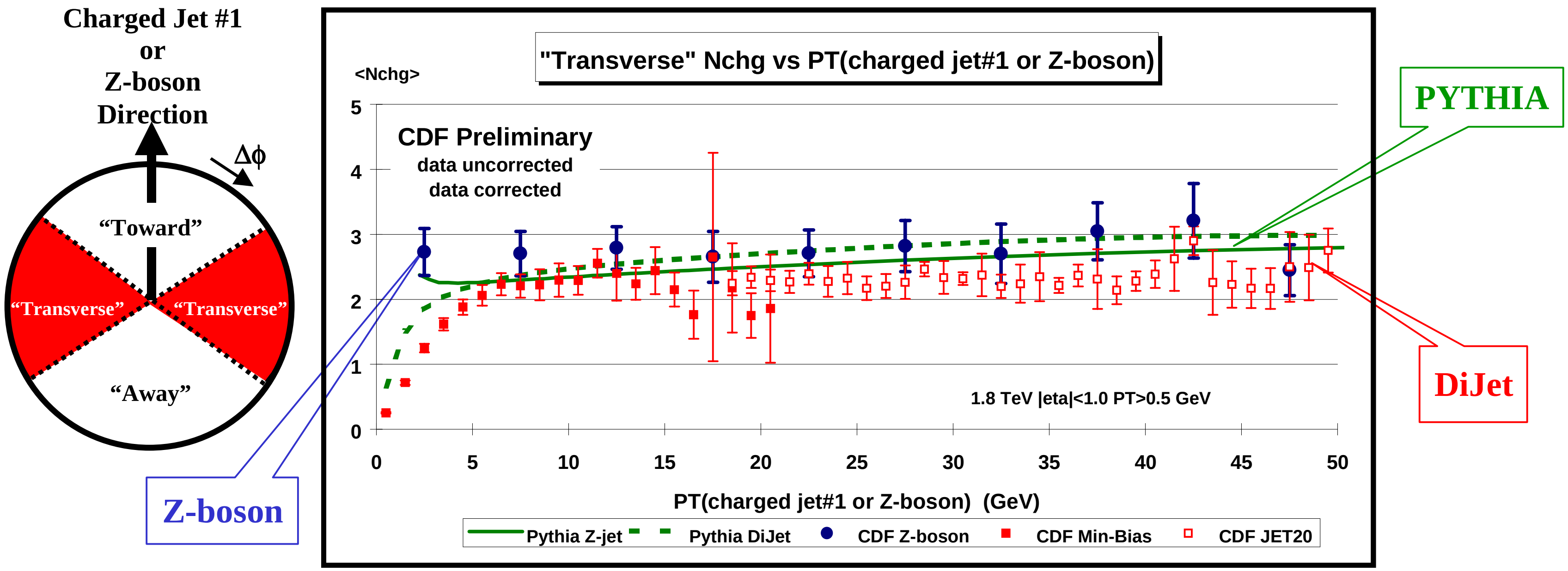
- ⇨ Comparison of the dijet and the Z-boson data on the average number of charged particles (P_T > 0.5 GeV, |η| <1) for the “away” region.
- ⇨ The plot shows the QCD Monte-Carlo predictions of PYTHIA 6.115 for dijet (dashed) and “Z-jet” (solid) production.

DiJet vs Z-Jet "Transverse" Nchg



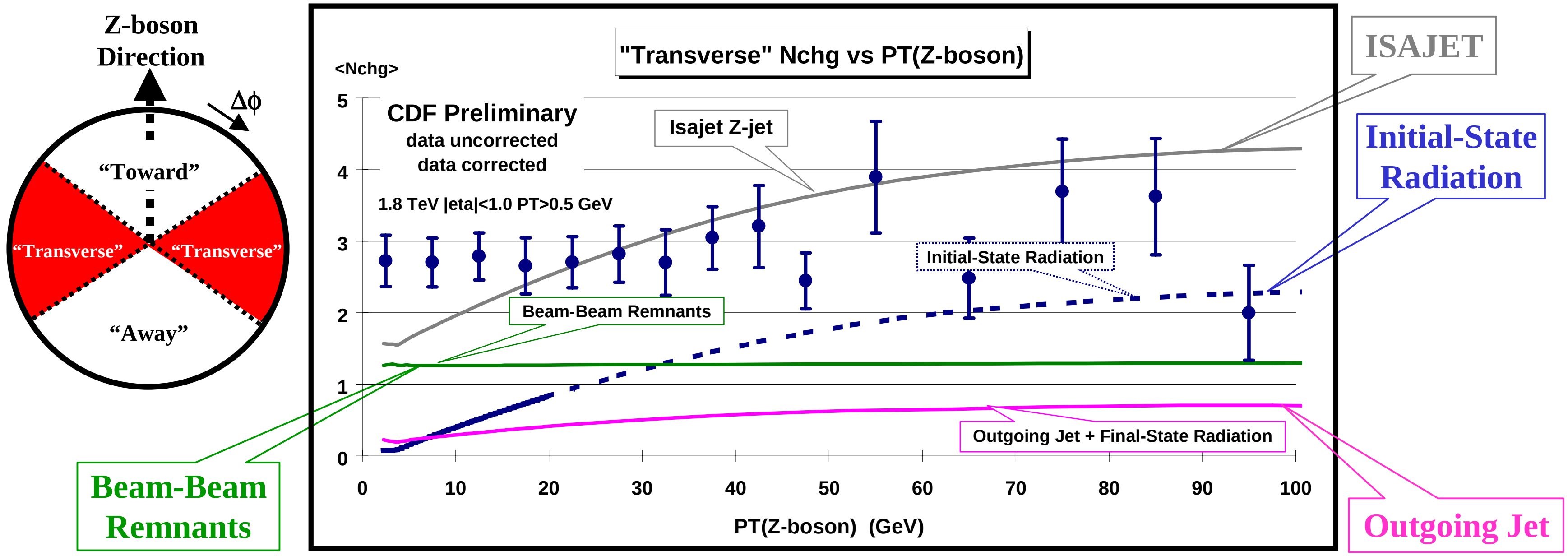
- Comparison of the dijet and the Z-boson data on the average number of charged particles (P_T > 0.5 GeV, $|\eta|$ <1) for the "transverse" region.
- The plot shows the QCD Monte-Carlo predictions of ISAJET 7.32 for dijet (dashed) and "Z-jet" (solid) production.

DiJet vs Z-Jet "Transverse" Nchg



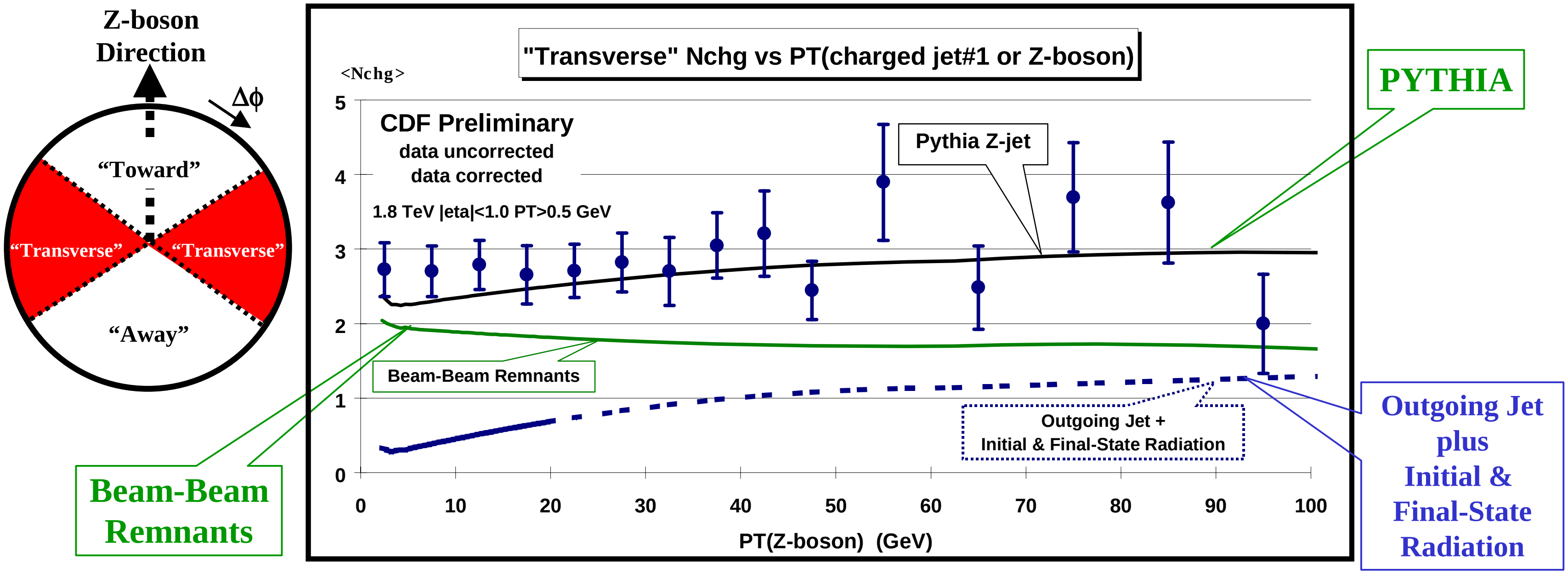
- Comparison of the dijet and the Z-boson data on the average number of charged particles ($P_T > 0.5$ GeV, $|\eta| < 1$) for the "transverse" region.
- The plot shows the QCD Monte-Carlo predictions of PYTHIA 6.115 for dijet (dashed) and "Z-jet" (solid) production.

Z-boson: “Transverse” Nchg versus PT(Z)



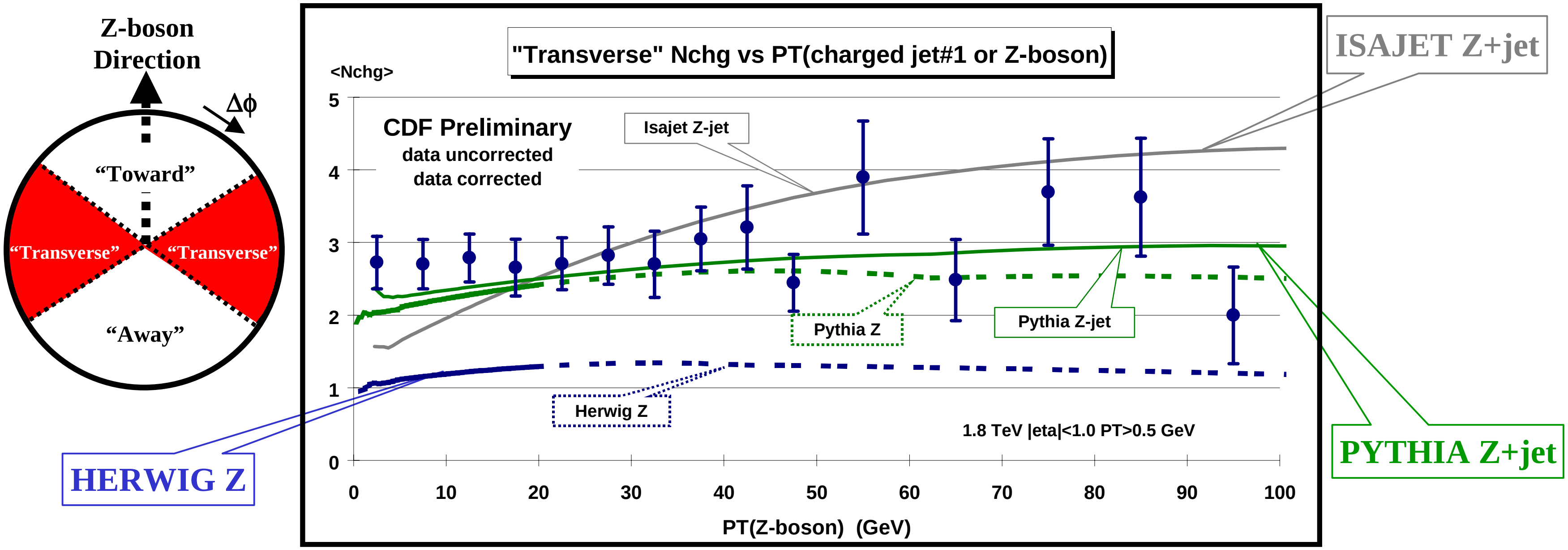
- Plot shows the Z-boson “transverse” <Nchg> vs P_T(Z) compared to the “Z+jet” QCD Monte-Carlo predictions of ISAJET 7.32.
- The predictions of ISAJET are divided into three categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants), charged particles that arise from initial-state radiation, and charged particles that result from the outgoing jets plus final-state radiation.

Z-boson: "Transverse" Nchg versus PT(Z)



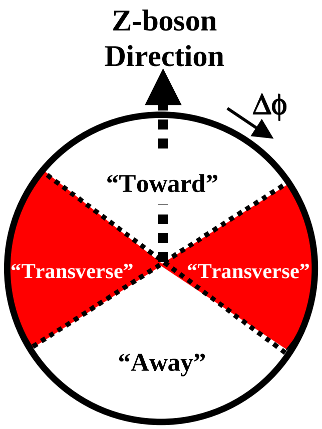
- Plot shows the Z-boson "transverse" <Nchg> vs P_T(Z) compared to the "Z+jet" QCD Monte-Carlo predictions of PYTHIA 6.115.
- The predictions of PYTHIA are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).

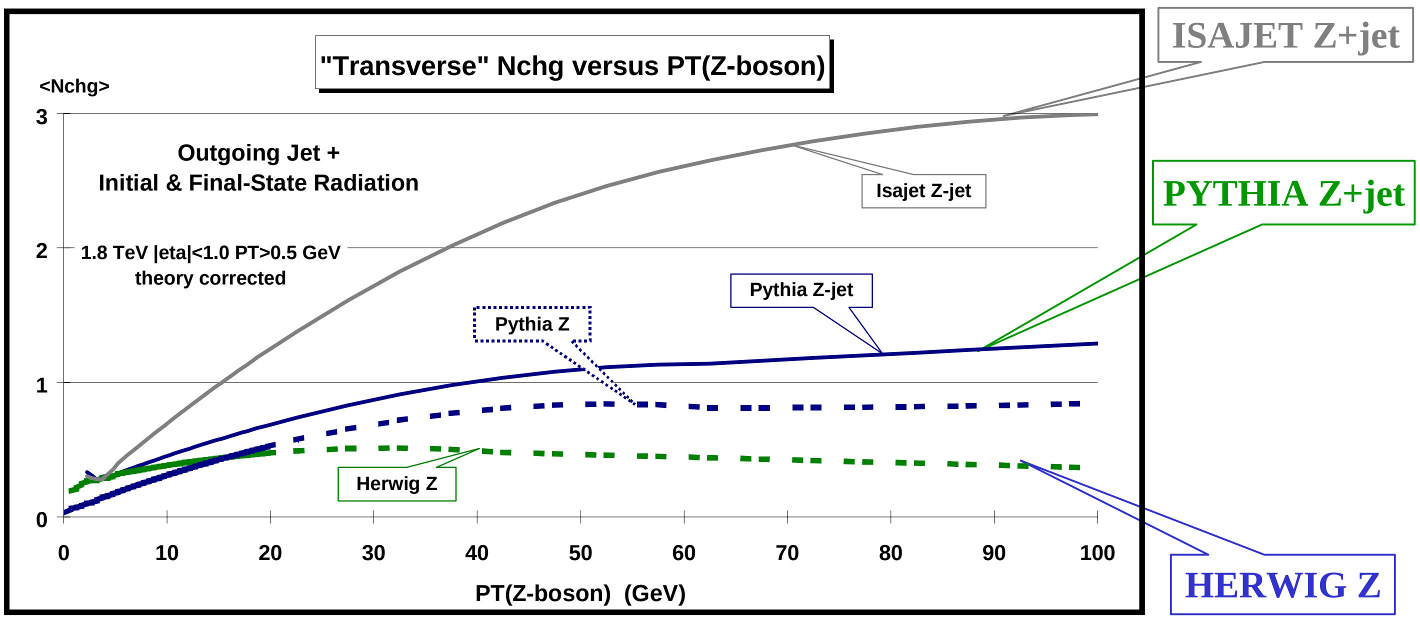
Z-boson: “Transverse” Nchg versus PT(Z)



- **Z-boson** data on the average number of charged particles ($P_T > 0.5$ GeV and $|\eta| < 1$) as a function of $P_T(Z)$ for the **“transverse”** region compared with the QCD Monte-Carlo predictions of **HERWIG 5.9 (“Z”)**, **ISAJET 7.32 (“Z-jet”)**, and **PYTHIA 6.115 (“Z”, “Z-jet”)**.

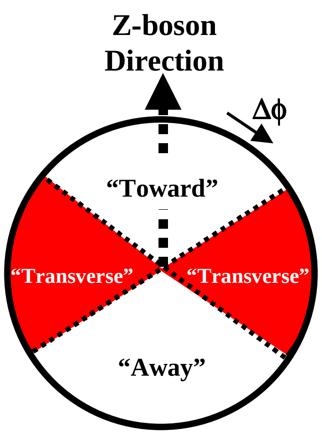
Z-boson: “Transverse” Nchg versus PT(Z)

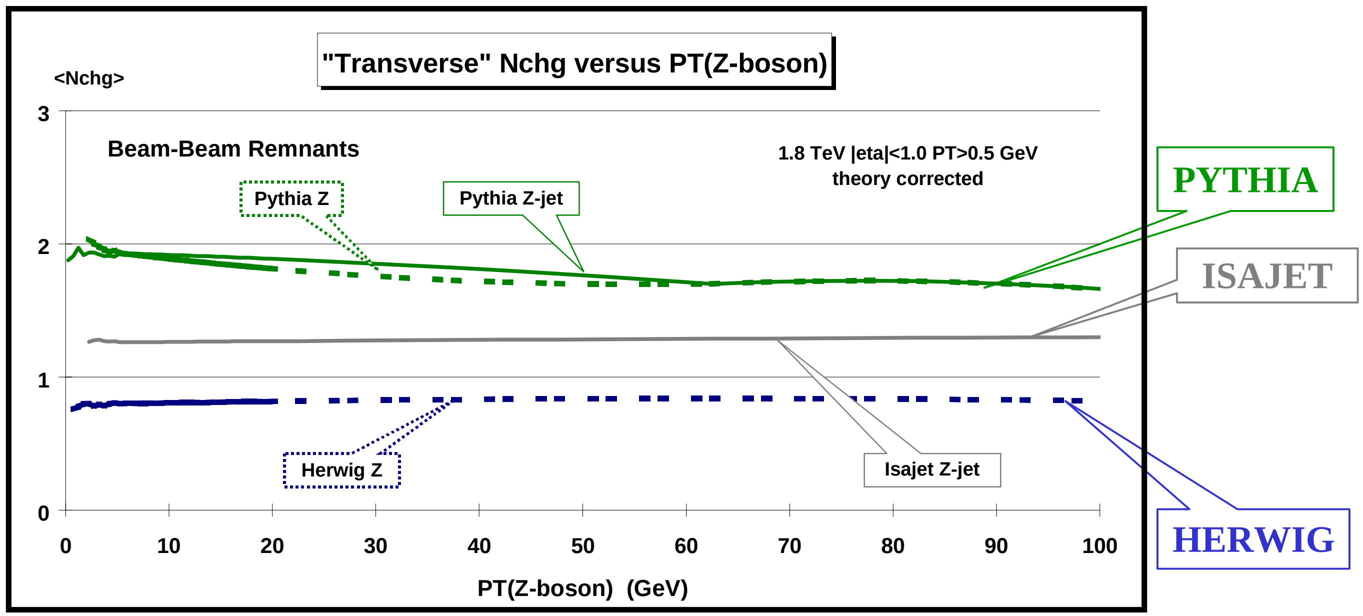




- **QCD Monte-Carlo predictions of HERWIG 5.9 (“Z”), ISAJET 7.32 (“Z-jet”), and PYTHIA 6.115 (“Z”, “Z-jet”).**
- **Plot shows the Z-boson “transverse” <Nchg> vs $P_T(Z)$ arising from the outgoing jets plus initial and finial-state radiation (hard scattering component).**
- **Same effect seen in dijet production.**

Z-boson: “Transverse” Nchg versus PT(Z)





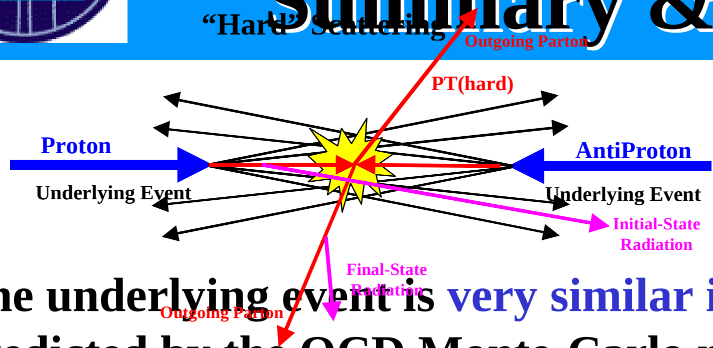
- QCD Monte-Carlo predictions of HERWIG 5.9 (“Z”), ISAJET 7.32 (“Z-jet”), and PYTHIA 6.115 (“Z”, “Z-jet”).
- Plot shows the Z-boson “transverse” <Nchg> vs $P_T(Z)$ arising from the beam-beam remnants. For PYTHIA the beam-beam remnants include contributions from multiple parton scattering.

Charged Particle Jets: Summary & Conclusions

The Evolution of "Charged Jets"

- **Charge particle jets (R = 0.7) are "born" somewhere around P_T of about 1 GeV with, on the average, about 2 charged particles, and grow to, on the average, about 10 charged particles at 50 GeV.**
- **The QCD hard-scattering Monte-Carlo models agree qualitatively well with the multiplicity distribution of the charged particles within a jet, the distribution of charged multiplicity and PTsum around the jet direction, the size of the jets, and momentum distribution of charged particles within the jet. They agree as well with 2 GeV jets as they do with 50 GeV jets!**
- **The charged jets in the Min-Bias data are simply the extrapolation (*down to small P_T*) of the high transverse momentum jets observed in the JET20 data. The Min-Bias data are a mixture of "hard" and "soft" and to completely describe the data will require combining a model for the "soft" collisions with a QCD perturbative Monte-Carlo model of the "hard" collisions.**

The Underlying Event: Summary & Conclusions



The "Underlying Event"

- The underlying event is very similar in dijet and the Z-boson production as predicted by the QCD Monte-Carlo models. The "toward" region in Z-boson production is a direct measure of the underlying event.
- The number of charged particles per unit rapidity (height of the "plateau") is at least twice that observed in "soft" collisions at the same corresponding energy.
- None of the QCD Monte-Carlo models correctly describe the underlying event. Herwig and Pythia 6.125 do not have enough activity in the underlying event. Pythia 6.115 has about the right amount of activity in the underlying event, but as a result produces too much overall multiplicity. Isajet has a lot of activity in the underlying event, but with the wrong dependence on P_T(jet#1) or P_T(Z). None of the Monte-carlo models have the correct P_T dependence of the beam-beam remnant component of the underlying event.